A coupled large-scale model for hydromechanical simulation of CO2 geological storage

Pierre Sochala, Vivien Desveaux, Darius Seyedi, Jeremy Rohmer

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* BRGM (French Geological Survey)
Natural Risks and Safety of CO_2 storage
Orléans

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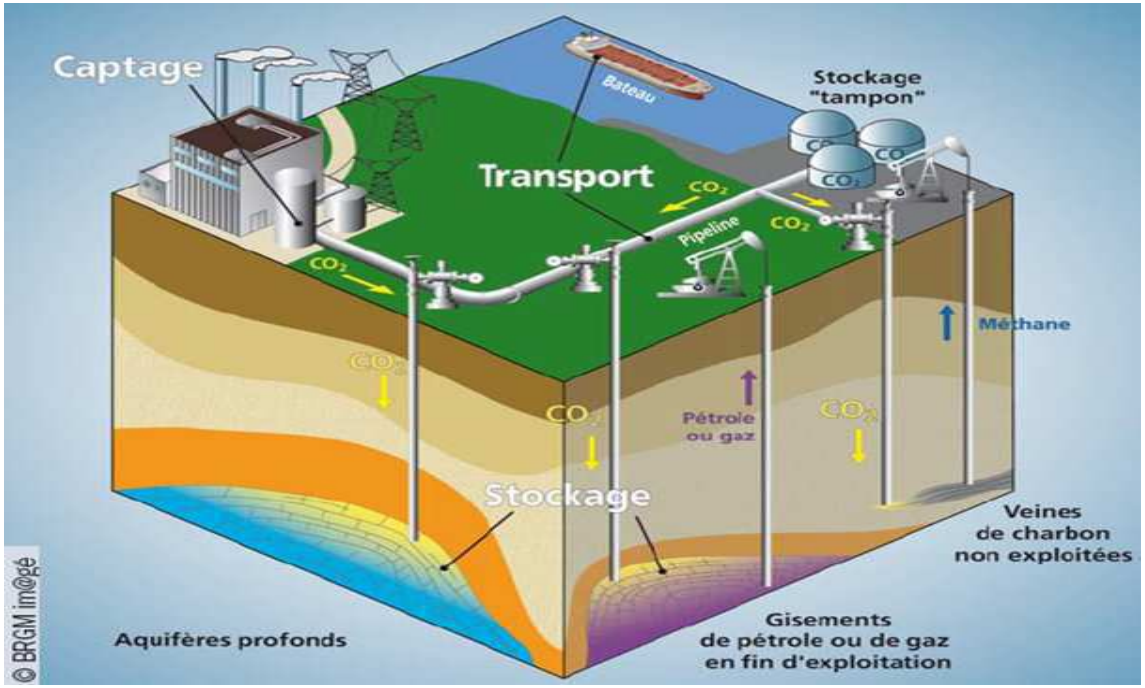
General introduction

Greenhouse gas emissions $\Rightarrow$ Global warming



CO_2 injection $\Rightarrow$ reservoir overpressure $\Rightarrow$ caprock damage or fault reactivation ?

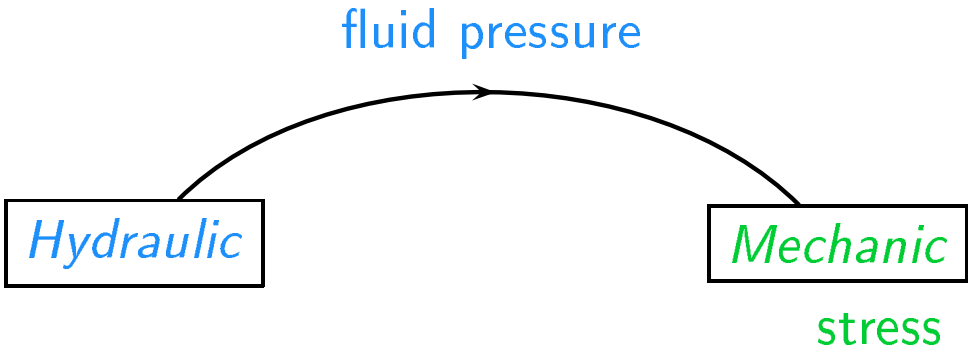
General introduction

Hydraulic *Mechanic*

Hydromechanical modeling of CO_2 sequestration

- Tough2 - FLAC^{3D} $\longrightarrow$ *Rutqvist et al.*
- ToughReact - FLAC^{3D} $\longrightarrow$ *Taron et al.*
- Modified CODE_BRIGHT $\longrightarrow$ *Vilarrasa et al.*
- ATH2VIS $\longrightarrow$ *Mainguy et al.*

General introduction



Hydromechanical modeling of CO_2 sequestration

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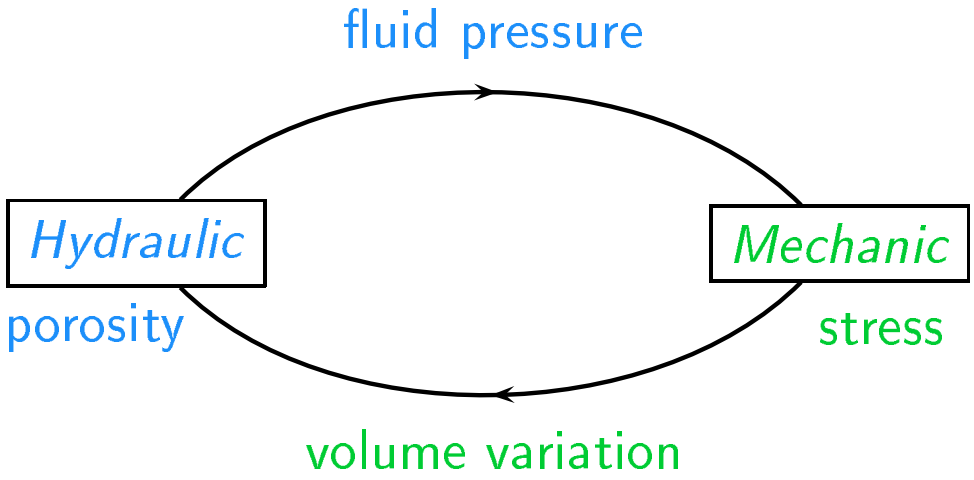

Hydromechanical modeling of CO_2 sequestration

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Geohydrological system

- Two-phase γ (liquid, gaz) and two-component χ (water, CO_2) flow
- **Mass conservation** of χ with a source term S_χ

$$\partial_t \left(\varphi \sum_\gamma \rho_\gamma s_\gamma \omega_{\chi,\gamma} \right) + \nabla \cdot \left(\sum_\gamma \omega_{\chi,\gamma} F_\gamma \right) = S_\chi$$

φ porosity, ρ_γ density, s_γ saturation, $\omega_{\chi,\gamma}$ mass fraction of χ in γ

- **Darcy's law**

$$F_\gamma = -\rho_\gamma \frac{k_\mathrm{i} k_{\mathrm{r},\gamma}}{\mu_\gamma} (\nabla p_\gamma - \rho_\gamma g e_z)$$

k_i porous media intrinsec permeability, $k_{\mathrm{r},\gamma}$ relative permeability
μ_γ dynamic viscosity, p_γ pressure

- Hydraulic relations $\longrightarrow$ *Van-Genuchten80, Mualem76*
  Thermodynamic equilibrium $\longrightarrow$ *Spycher&Pruess05*

Mechanical equations

- **Conservation of momentum**

$$\nabla \cdot \sigma + \rho g e_z = 0$$

σ total stress tensor, ρ average density

- **Effective stress concept**

$$\sigma = \sigma' - bpI$$

σ' effective stress tensor, b Biot's coefficient, p pore pressure

- **Linear elasticity**

$$\sigma' = \frac{E}{1+\nu}\left(\nabla u + {}^t\nabla u + \frac{\nu}{1-2\nu}(\nabla \cdot u)I\right)$$

E Young's modulus, ν Poisson's ratio, u displacement

Coupling conditions

- **pore pressure** equal to the mean-value of the two-phase system

$$p = \sum_{\gamma} s_\gamma p_\gamma$$

- **permeability-porosity relation** $\rightarrow$ *David05*

$$k_{\mathrm{i}} = k_{\mathrm{i}}^0 \left(\frac{\varphi}{\varphi^0} \right)^m$$

m empirical parameter

- **Biot's law** $\rightarrow$ *Biot41*

$$d\varphi = b d(div(u)) + \frac{1}{M} dp$$

M Biot's modulus

Tough2 and Code_Aster discretization

Tough2 → Lawrence Berkeley National Laboratory

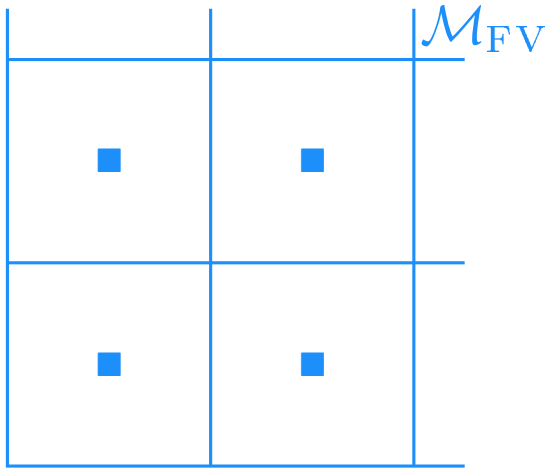
- Multi-phase fluid and heat flow in porous and fractured media
- **Finite volume** with finite difference evaluation of the flux term
  Integrated Finite Difference Method → Narasimham76
- Euler implicit scheme
- Newton Raphson Algorithm

Code_Aster → EDF (French Electricity Compagny)

- Non-linear models of mechanical phenomena
- **Finite element**

Transfer operator $\mathcal{T}_{\mathrm{FV}\to\mathrm{FE}}$ for pressure field

step 1 - construction of a dual mesh



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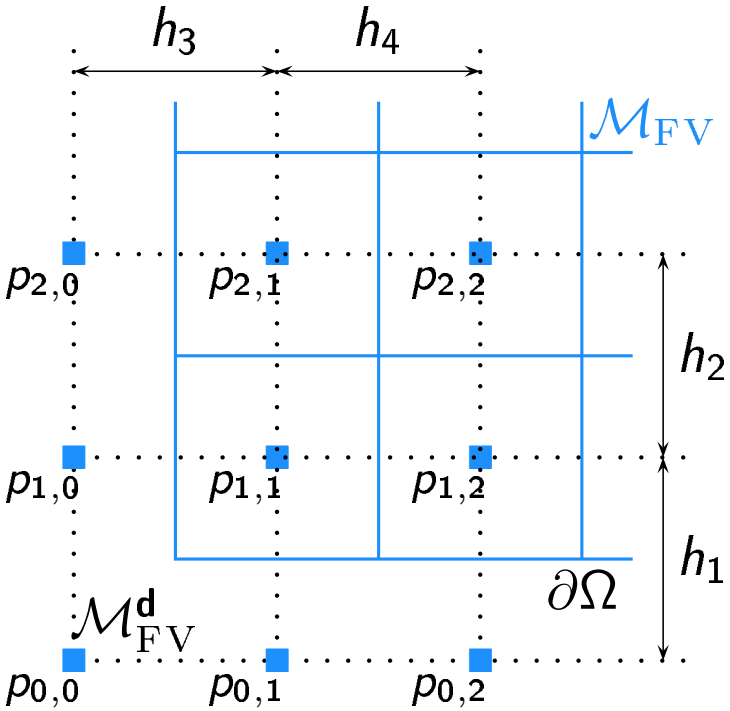
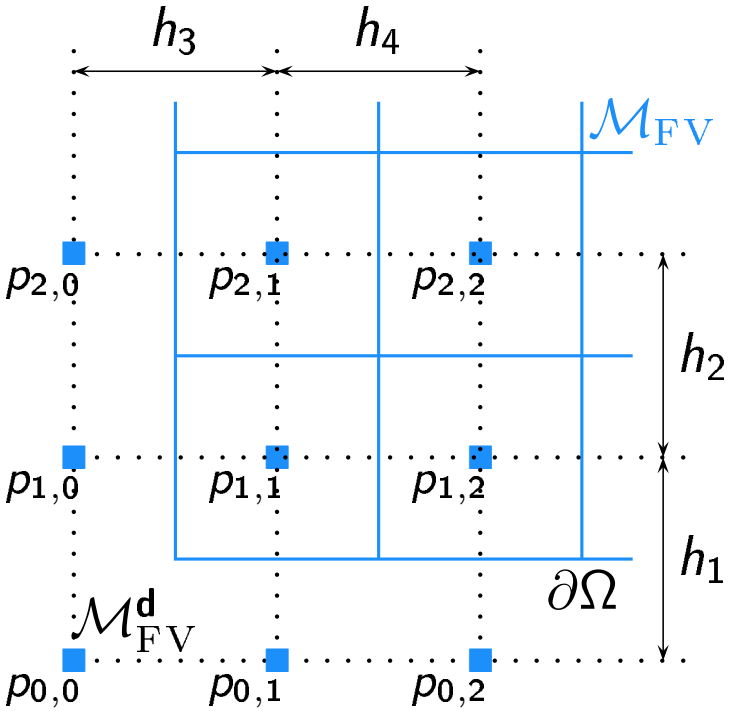


$$p_{0,i} = p_{1,i} + \frac{h_1}{h_2}(p_{1,i} - p_{2,i})$$

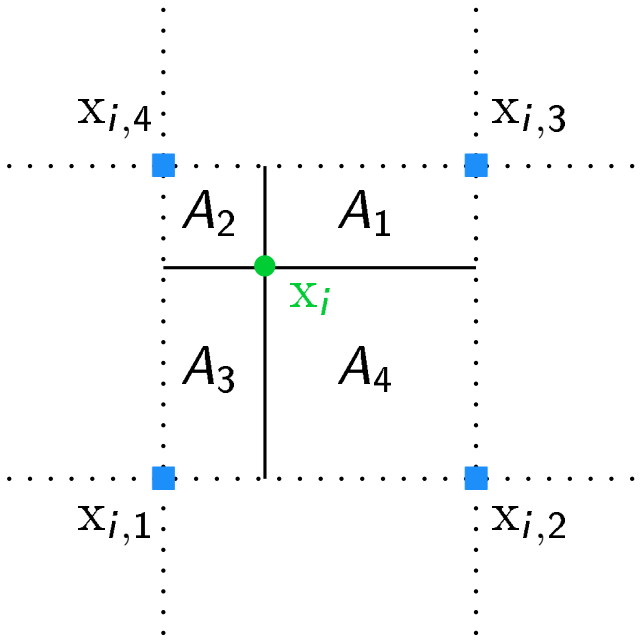
Transfer operator $\mathcal{T}_{\mathrm{FV}\to\mathrm{FE}}$ for pressure field

step 1 - construction of a dual mesh



$$p_{0,i} = p_{1,i} + \frac{h_1}{h_2}(p_{1,i} - p_{2,i})$$

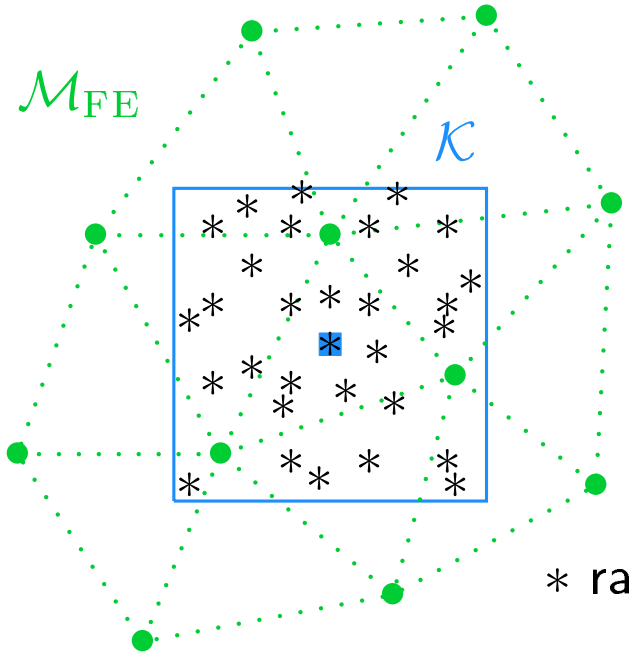
step 2 - linear interpolation



$$p_{\mathrm{FE}}(\mathrm{x}_i) = \sum_{k=1}^{4} \frac{A_k}{A} p_{\mathrm{FV}}(\mathrm{x}_{i,k})$$

Transfer operator $\mathcal{T}_{\mathrm{FE}\to\mathrm{FV}}$ for porosity field

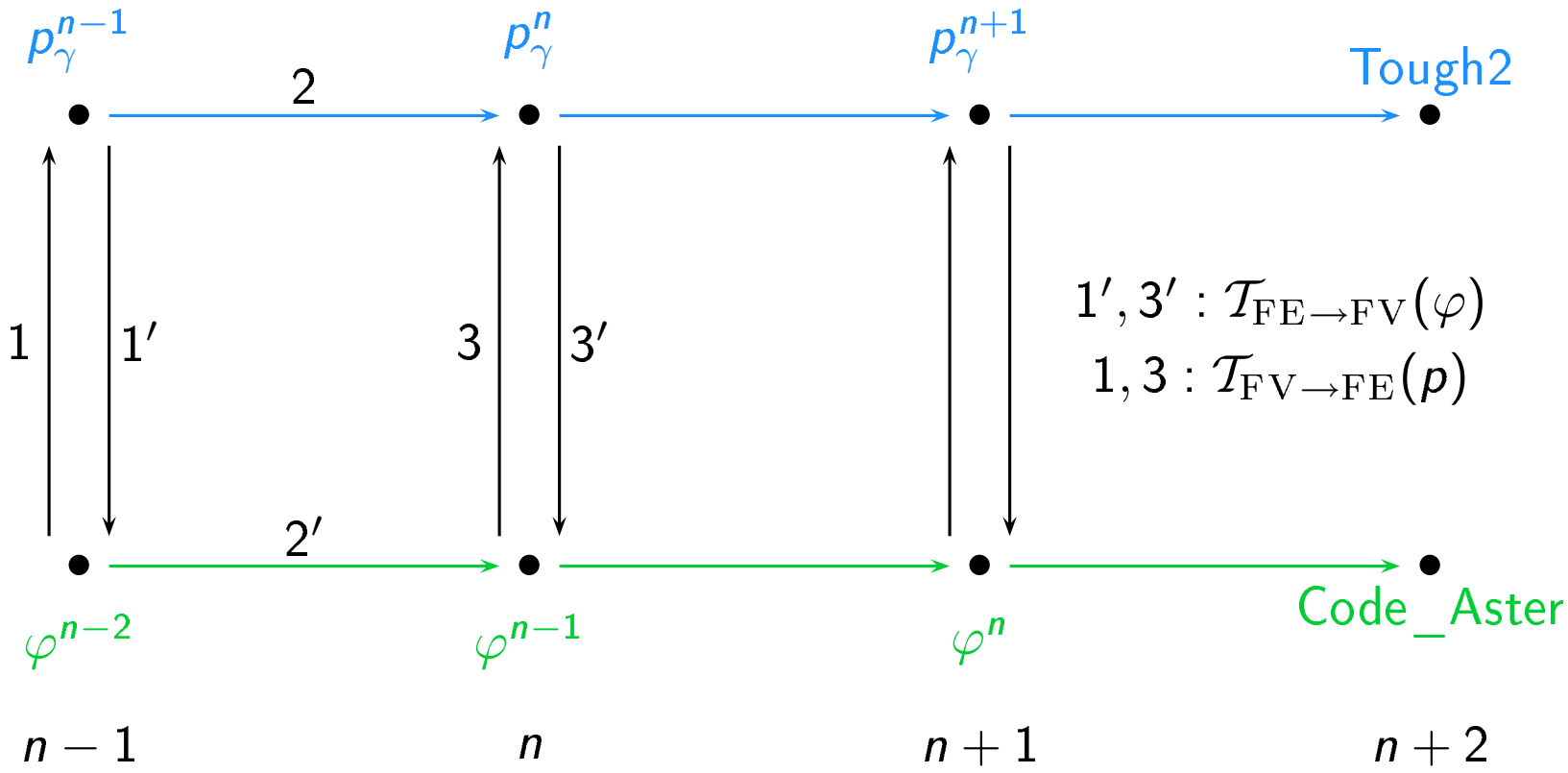
Mean-value of φ on $\mathcal{K}$ estimated by MC



$$\varphi_{\mathrm{FV}}|_{\mathcal{K}} = \frac{1}{N}\sum_{j=1}^{N}\varphi_{\mathrm{FE}}(\mathrm{x}_j)$$

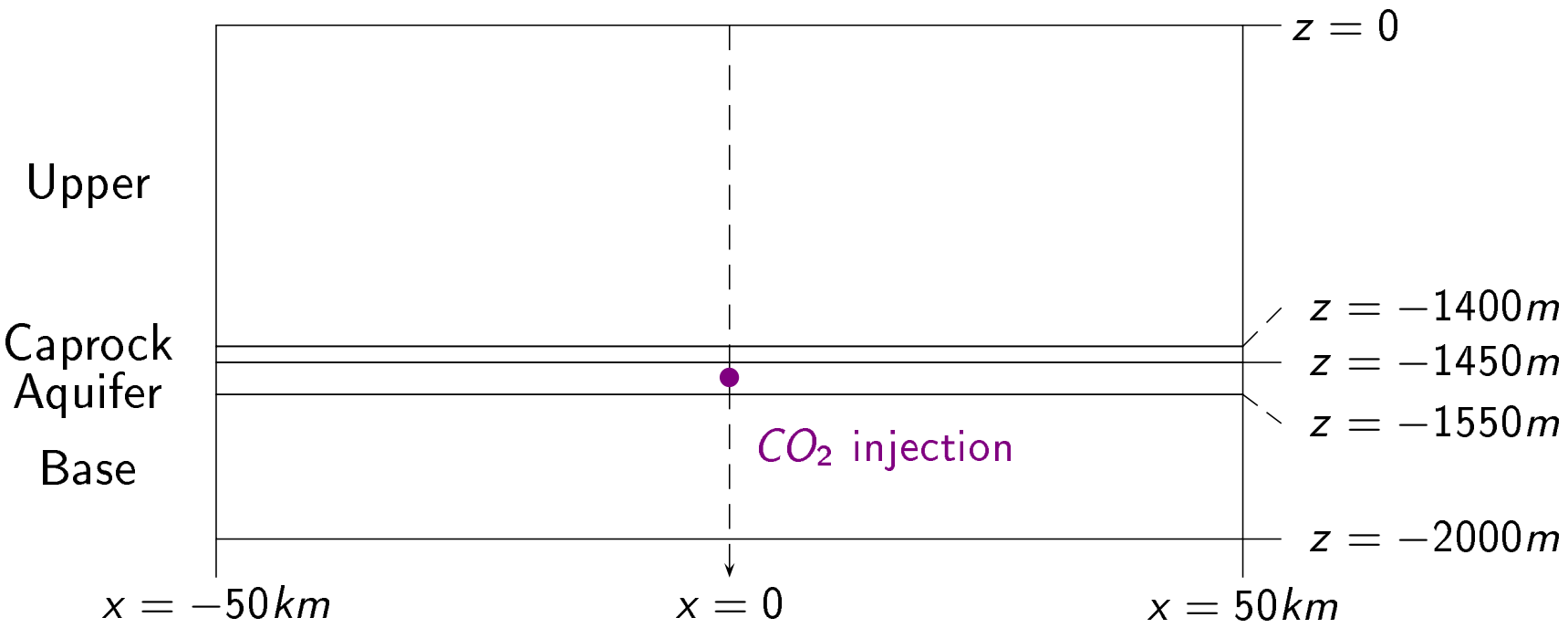
Time coupling

Conventional **P**arralel **S**taggered algorithm → *Piperno et al 95*



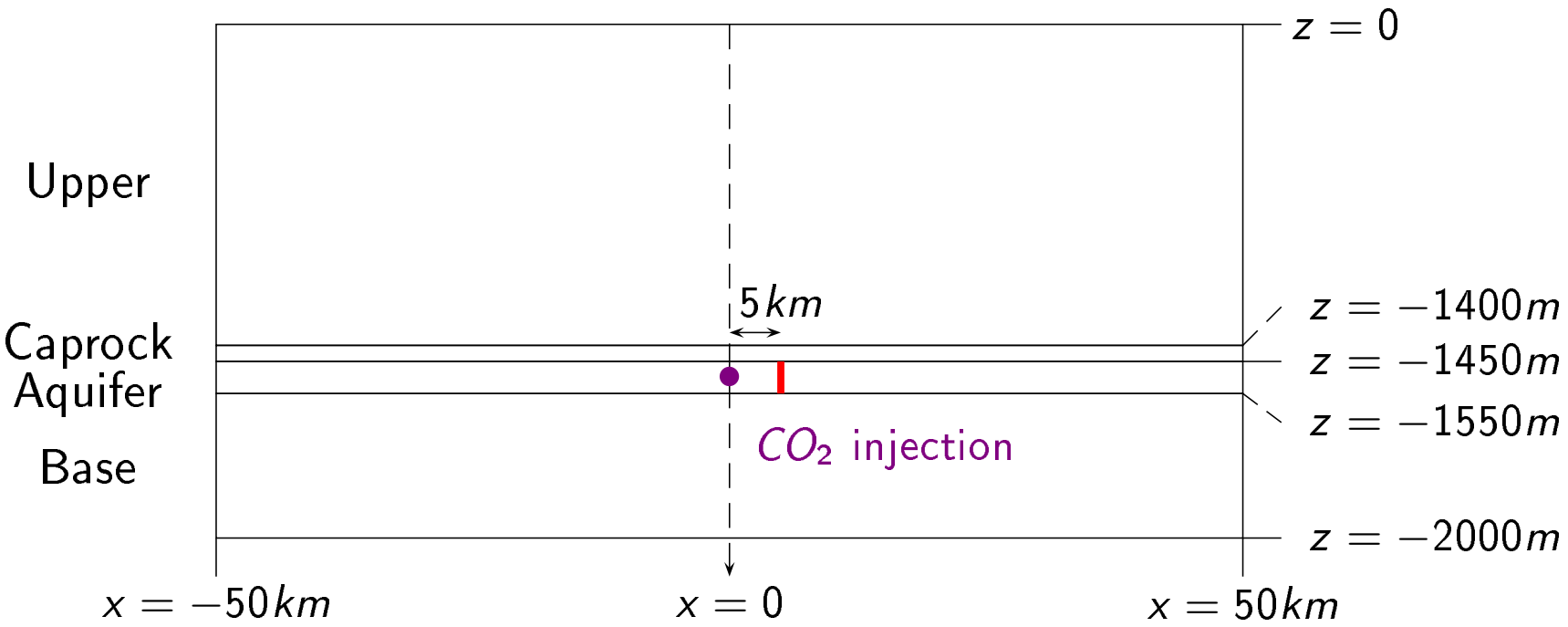
Test case presentation

- CO_2 injection by horizontal well in deep aquifer
- 2D geometry $\Omega = [-50km, 50km] \times [0, -2km]$ and $T = 5years$
- $S_{CO_2} = 500t/m/year$
-



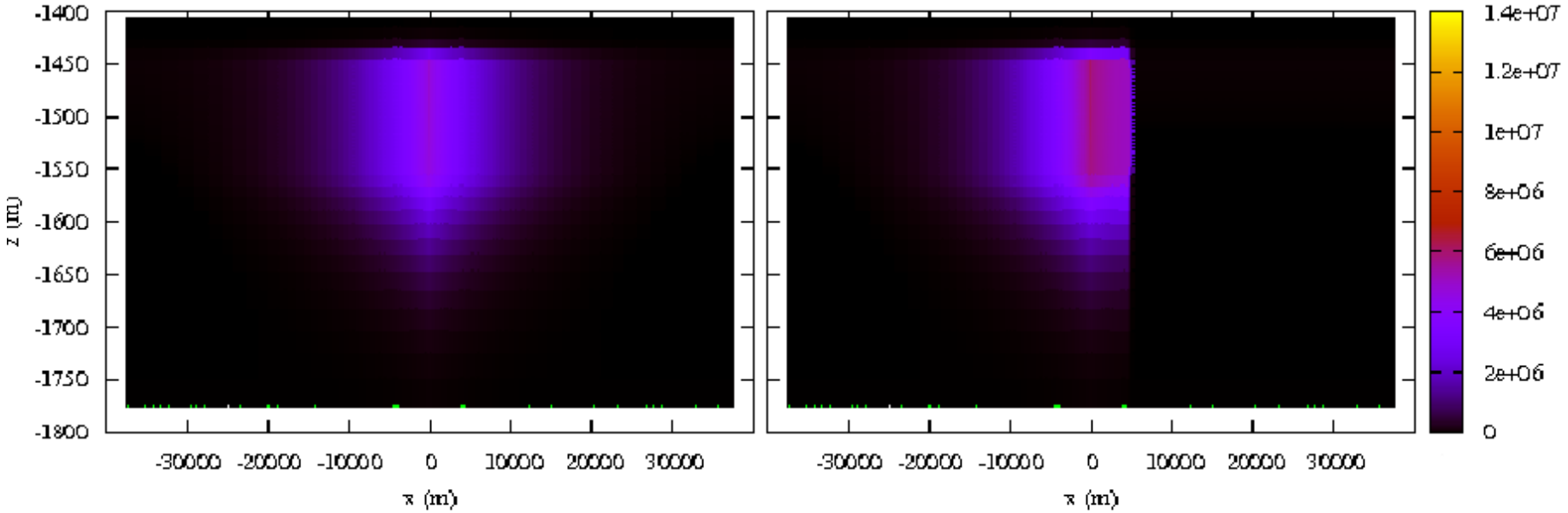
Test case presentation

- CO_2 injection by horizontal well in deep aquifer
- 2D geometry $\Omega = [-50km, 50km] \times [0, -2km]$ and $T = 5years$
- $S_{CO_2} = 500t/m/year$
- impact of a sealing fault near the injection zone



Overpressure (Pa)

t=1 year

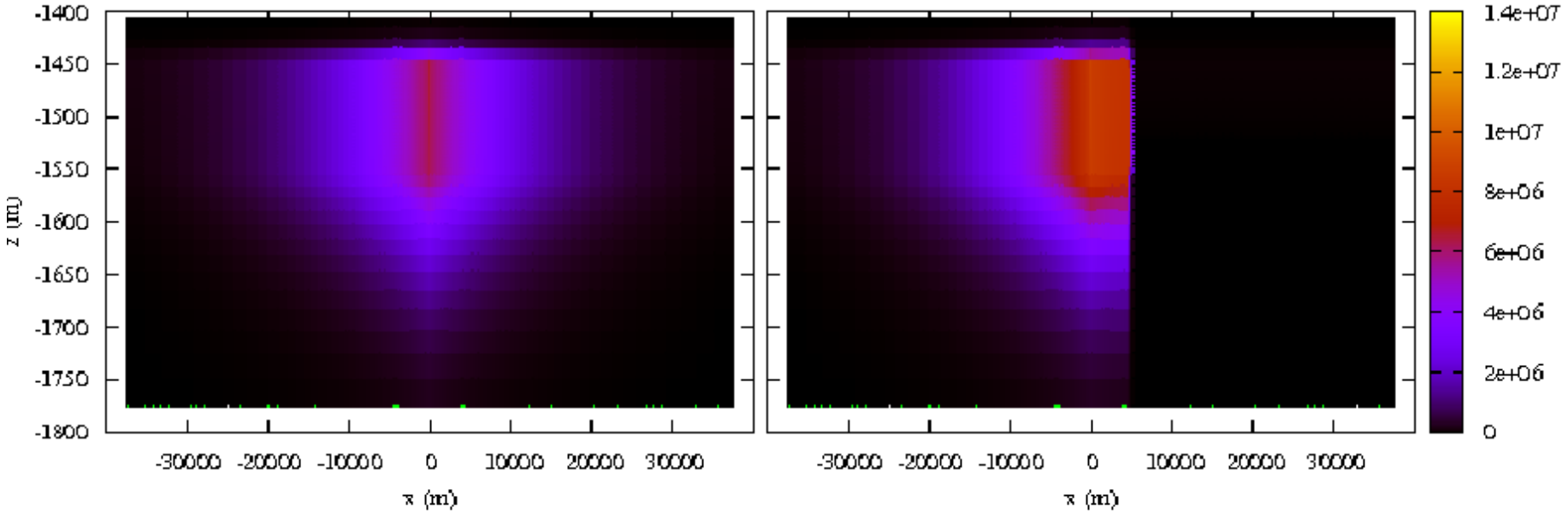


Initial case

Perturbated case

Overpressure (Pa)

t=2 years

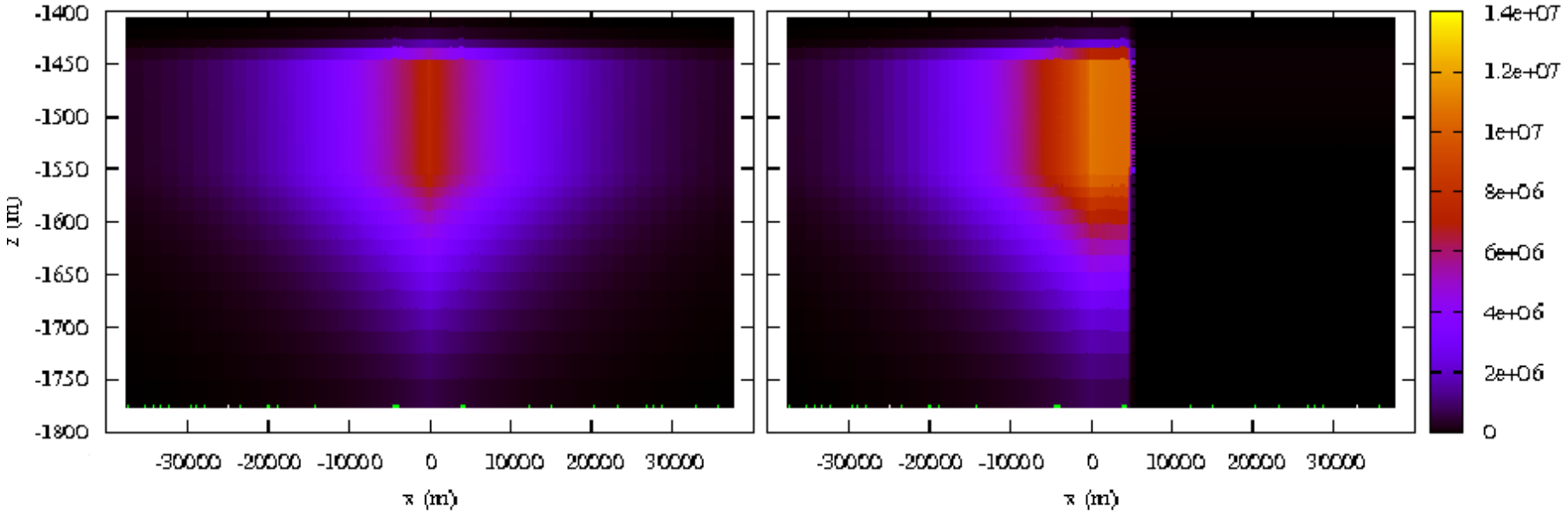


Initial case

Perturbated case

Overpressure (Pa)

t=3 years

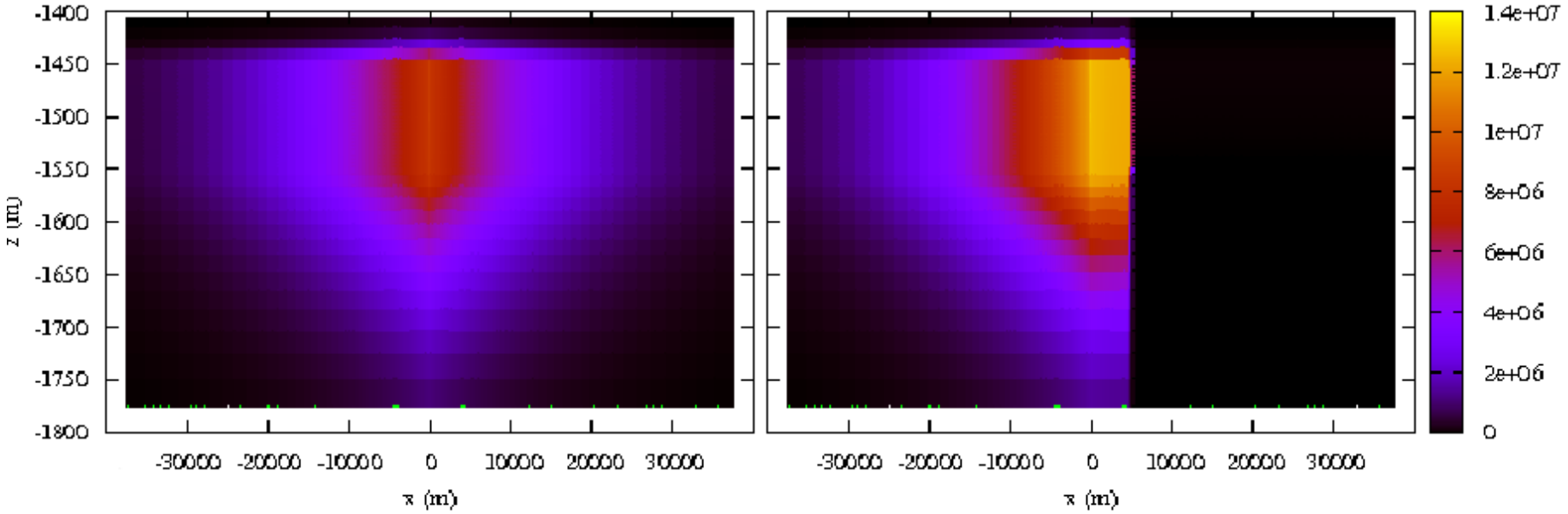


Initial case

Perturbated case

Overpressure (Pa)

t=4 years

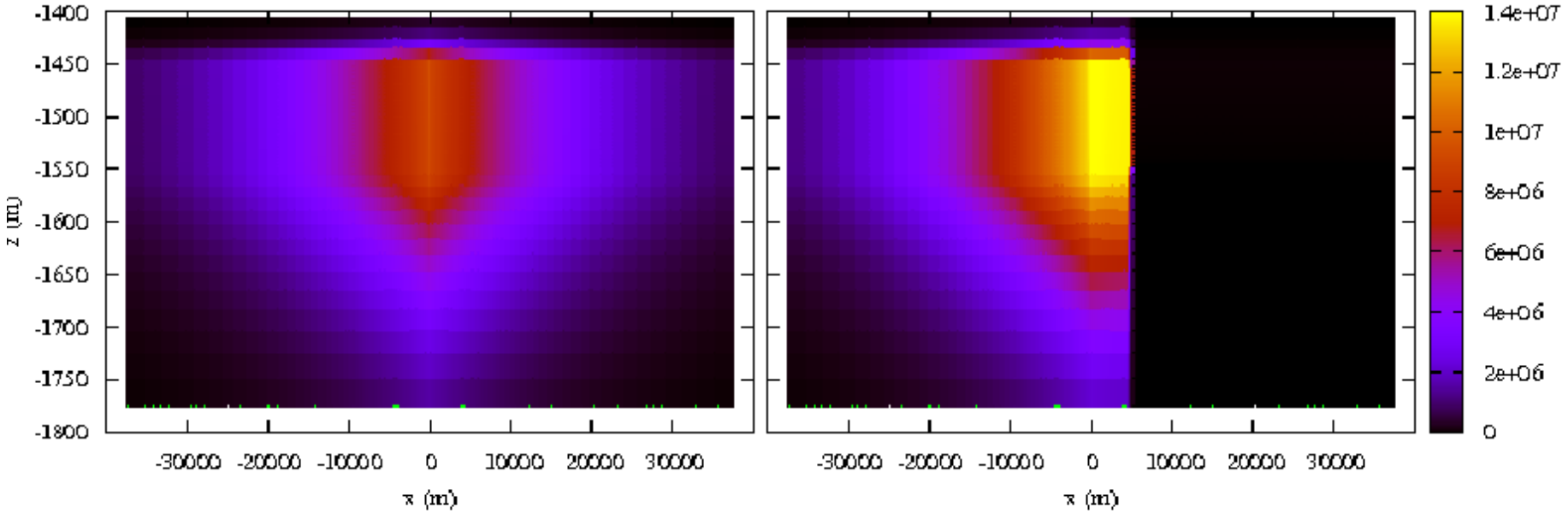


Initial case

Perturbated case

Overpressure (Pa)

t=5 years

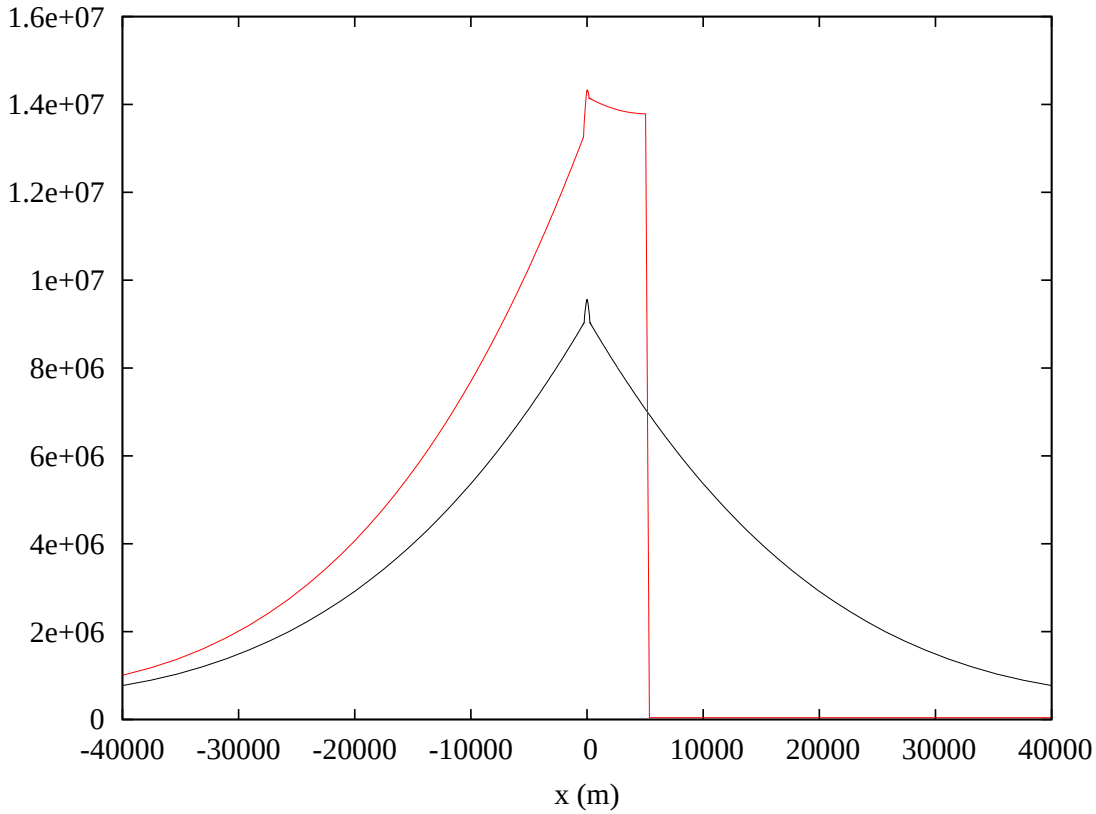


Initial case

Perturbated case

Overpressure in the aquifer (Pa)

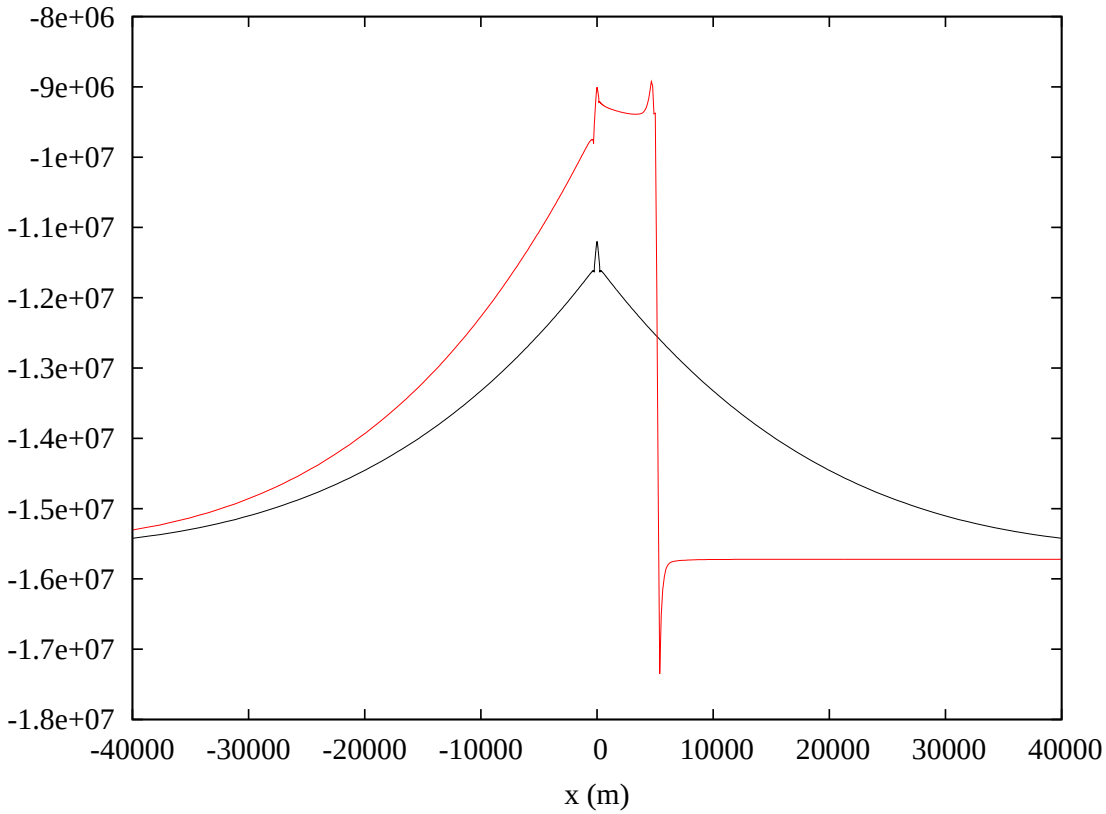
Initial case Perturbated case



Increase of 40% of the overpressure at 5 years

Horizontal effective stress change due to injection (Pa)

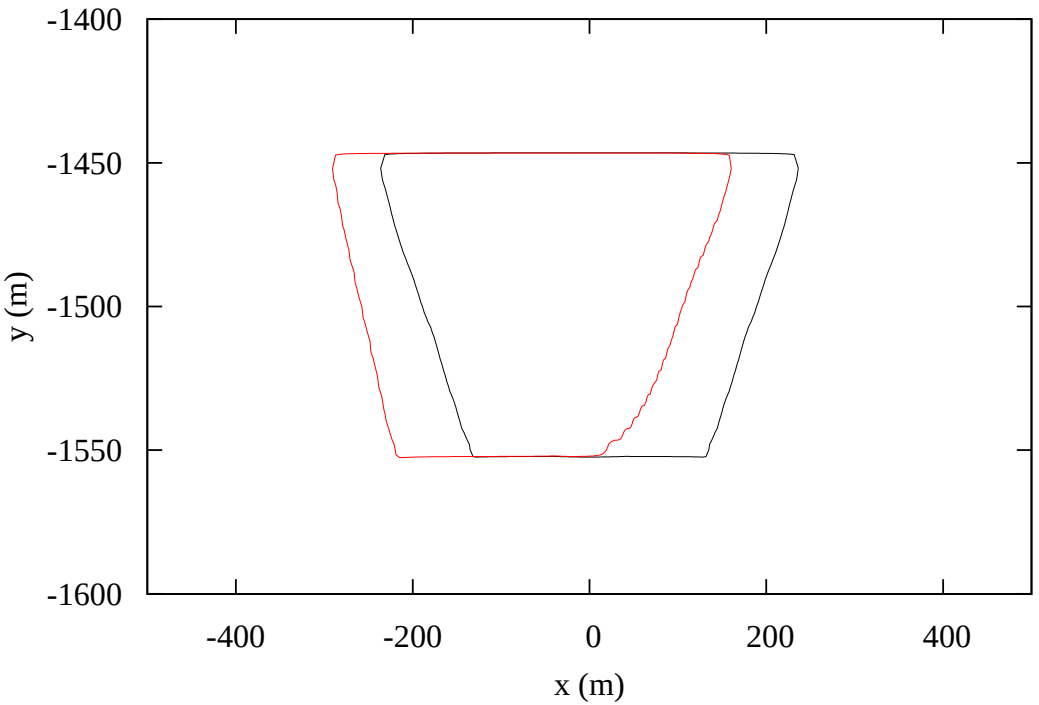
Initial case Perturbated case



More change in effective stress

CO_2 plume

Initial case Perturbated case



Displacement at the opposite side of the fault

Conclusion

- robust method to transfer fields between different meshes
- efficient parallel time coupling algorithm
- significant increase of the overpressure due to the impermeable fault

Further work

- tensile and shear stress failure criteria $\longrightarrow$ sustainable pressure
- non-linear constitutive law of the geological formation
- more realistic geometry